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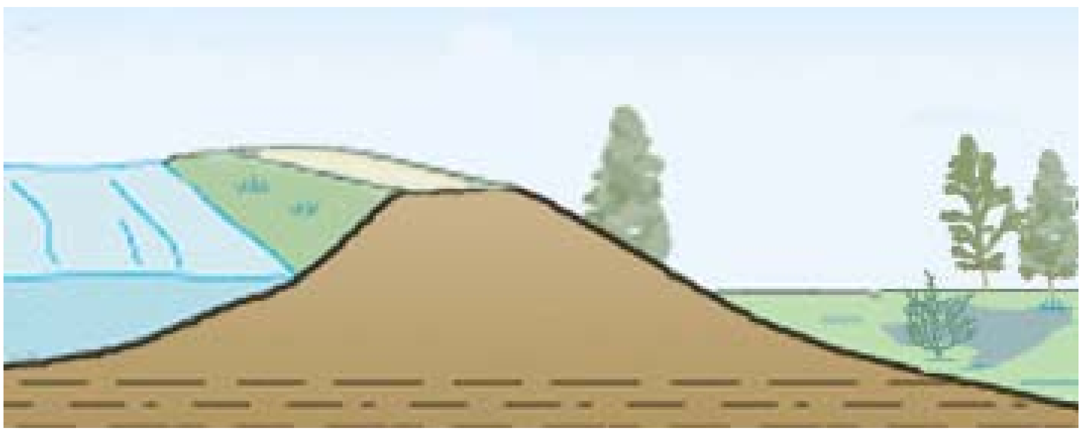
Suisun Marsh Charter Group
Levee Conceptual Model

State of Knowledge



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the

Habitat Management, Preservation, and Restoration Plan for
Suisun Marsh

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Suisun Marsh Charter Group Principal Agencies

US FISH AND WILDLIFE SERVICE
US BUREAU OF RECLAMATION
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION FISHERIES SERVICE
DEPARTMENT OF FISH AND GAME
DEPARTMENT OF WATER RESOURCES
CALIFORNIA BAY-DELTA AUTHORITY
SUISUN RESOURCE CONSERVATION DISTRICT

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Overview

The Habitat Management, Preservation, and Restoration Plan for Suisun Marsh (Suisun Marsh Plan) is a multi-agency cooperative effort among state, federal, and local agencies, and private landowners to protect and enhance wildlife values, and water quality in the Suisun Marsh. A critical component of this effort is the development of conceptual models to describe the current state of knowledge, existing conditions, and effects of stressors on those conditions. The levee conceptual model will be used in conjunction with additional conceptual models being develop for Suisun Marsh in order to integrate technical information into decisions for habitat management, preservation, and restoration plans for Suisun Marsh. This model begins to identify linkages to other conceptual models being prepared for the Suisun Marsh Plan. It will expand those linkages and be adapted over time in conjunction with development of these other conceptual models. The conceptual models will be used to study the effects of changing conditions, test alternative restoration concepts, and guide implementation of the Suisun Marsh Plan.

While the CALFED Levee Program consists of two main components - Delta Levees and Suisun Marsh Levees (CBDA, 2005), the levees in Suisun Marsh are uniquely different from those in the Delta. This conceptual model focuses on Suisun Marsh levees in an effort to provide an understanding of this levee system that can lead to identification of specific actions and alternatives, including development of a levee program under the Suisun Marsh Plan.

The levee conceptual model begins with an introductory background of levees in the marsh and includes the following elements:

- Levees as Protection of Habitat and as Habitat: describes attributes, functions and changes over time.
- Natural and Anthropogenic Processes: describes critical processes affecting levee stability.
- Levee Stability Stressors: describes significant stressors that influence levee stability and failure.
- Linkages: describes the interactions between levee stability stressors and natural and anthropogenic processes associated with levees.
- Technical Uncertainties and Research Needs: describes areas of uncertainty, assumptions, data gaps, and research needs to address uncertainties.

- Conclusions/Recommendations:

Acknowledgements

The authors appreciate the efforts of the many reviewers on this conceptual model. The reviewer's comments contributed to the improvement of this conceptual model and in particular the identification of research needs necessary to enhance the current understanding of Suisun Marsh levees. In particular we wish to thank Cay Goude and Cecilia Brown (USFWS), Frank Wernette and Laurie Briden (DFG), Steve Chappell (SRCD), Lee Laurence (USBR), and Zach Hymanson (CBDA).

The authors also wish to thank Dan Ray (CBDA) for his efforts in coordinating the peer review and the three anonymous peer reviewers for their thoughtful reviews and helpful suggestions. While some comments related to the formation and implementation of a levee program for Suisun Marsh may not have been directly addressed in this conceptual model, that information will be considered in the development of a levee program under the Suisun Marsh Plan.

In addition, we wish to thank Stuart Siegel and Zach Hymanson for their efforts in the early conceptual model development process. Their assistance was valuable, not only for this model, but for other conceptual models that we have used in identifying linkages to assist in the integration of information for the Suisun Marsh Plan.

Glossary

Erosion – Loss of levee material due to the effects of channel flows, tidal action, boat wakes, and wind-generated waves.

Filter Fabric - Synthetic fabric, which allows water to pass through but prevents soil movement through the fabric.

Hydrostatic pressure – The pressure of water at a given depth resulting from the weight of the water above it.

Levee crown – The top surface between the slope edges of a levee.

Liquefaction – The process in which a saturated soil temporarily loses strength when subjected to ground vibrations as during an earthquake.

Non-project levee – A flood protection levee that is not a federal flood control project levee.

Oxidation – The conversion of organic soil, such as peat, to carbon dioxide.

Piping – The process of water seepage through or under levees, usually resulting in levee material being carried away.

Project levee – A flood protection levee which is part of a federal flood control project.

Reclamation District – A local agency responsible for maintenance of levees within the district boundaries.

Seepage – A slow movement of water through permeable soils caused by hydrostatic pressure.

Settlement – The lower ground elevations resulting from underlying soil consolidation caused by an increase in the weight of overlying deposits and or a decrease in water content in the soil primarily due to overpumping.

Slope protection – Various type of materials used to protect the levee surface and adjacent streambank from erosion.

Stability berm – Earth fill placed at the toe of the levee to prevent levee failure due to rotational slides.

Subsidence – The loss of soil within the first few feet of the surface due to organic soil oxidation, and topsoil erosion is referred to as shallow subsidence. Deep subsidence is caused by groundwater withdrawal and a decline of natural gas pressure.

Toe drain – A trench along the landside toe of the levee filled with crushed rock encapsulated in filter fabric. The toe drain reduces saturation of the levee, controls seepage, and prevents boils.

Introduction

Levees serve the primary function of flood control for Suisun Marsh infrastructure and natural resources. Exterior levees are used in conjunction with interior levees, ditches, and water control structures to retain and control water (DFG/SRCD 2004). The majority of the Suisun Marsh, including wildlife habitat, is situated at or below mean tide elevation. Exterior levees were constructed to protect managed wetlands, county and state lands, infrastructure, and residences from uncontrolled tidal inundation and flooding. Some levees were constructed on existing channel berms to take advantage of the existing natural topography throughout the Marsh. Levee configurations can vary considerably in material composition, cross-sectional geometry or shape, strength, stability or integrity. Alternate levee configurations serve various purposes and provide different levels of protection against tidal action or flood events within the Marsh. In many instances levees serve multiple purposes within the Marsh as important components of a highly modified estuary (Ramlit and Associates, 1983; Arnold, 1996; DWR, 1999, 2000, 2001).

Suisun Marsh levee failures result in serious local flooding and can cause local and regional increases in salinity. Flooding in the Marsh during 1998 and subsequent breach analysis modeling studies have demonstrated that Suisun Marsh levee failures can increase salinity in the Sacramento/San Joaquin Delta. Modeling research indicates ensuring the integrity of some exterior levees in the Suisun Marsh may be important to salinity and therefore water supply reliability in the Delta (DWR 2001). These modeling results indicate that large levee breaches on Suisun Bay tend to increase salinity in Suisun Bay and the Delta. Depending upon the location and extent of levee failures in Suisun Marsh, salt water intrusion into the Delta may place State-wide water supplies in jeopardy at least in the short-term (DWR 2001). These same studies also reveal possible opportunities for Delta water quality improvement with selected modifications to the Suisun Marsh levee system. Small levee breaches in certain locations in the Marsh may reduce regional Delta salinity. However, localized increases in Suisun Marsh salinity from these smaller breaches may require measures such as enhanced management practices to address any potential impacts resulting from increased salinity levels and tide stage. Although the Suisun Marsh Levee Investigation Team identified a significant link between Suisun Marsh levees, water quality, and water supply reliability, levees are not often considered part of the water distribution system. As result only a small portion of Suisun Marsh levees considered to have the greatest impact on Delta salinities and State lands/facilities are included in Assembly Bill 360, Delta Flood Protection and Delta Levee Maintenance.

Similarly, levees are not often considered part of the ecosystem even though they play a critical role in protecting and providing habitat(s) Mount, 1995; Arnold, 1996; Ingebritsen et al., 2000; Hart and Hunter, 2004; . Sudden failures of levees in the Marsh may flood areas that have subsided and may not be suitable for restoration into tidal wetlands and result in a loss of seasonal wetland habitat. Similar failures on Frank's Tract in the Delta demonstrated that long-lasting environmental and water quality impacts can result from unplanned levee failures. The creation of large unplanned open water areas can result uncertain changes in habitat for introduced or native species. In addition, a breach in exterior levees of Suisun Marsh can lead to failure of internal levees that are not built to withstand hydrostatic forces or overtopping similar to an exterior levee. Further levee failure and subsequent habitat changes could undermine the CALFED Ecosystem Restoration Program's ability to achieve its goals, objectives, and targets. For example, failure of levees in the Marsh may flood areas that are not suitable for restoration into tidal wetlands and result in changes to salinity and/or tidal stage that may limit opportunities to effectively restore more suitable areas. In contrast, improving critical levees can provide continued protection of managed wetlands and existing habitats already protected by these levees, and specific levee improvements may provide additional incremental protection against regional salinity intrusion as the result of specific levee failures (*sensu* DWR, 1999, 2000, 2001). In addition, improving specific levees can help ensure that conversion to tidal wetlands will not be due to levee failure but instead are planned in cooperation with other agencies and landowner support with consideration of protection of national, state, and regional infrastructure (such as highways and pipelines), Ecosystem Restoration Program targets, regional wetland goals, and endangered species recovery plans.

Assumptions

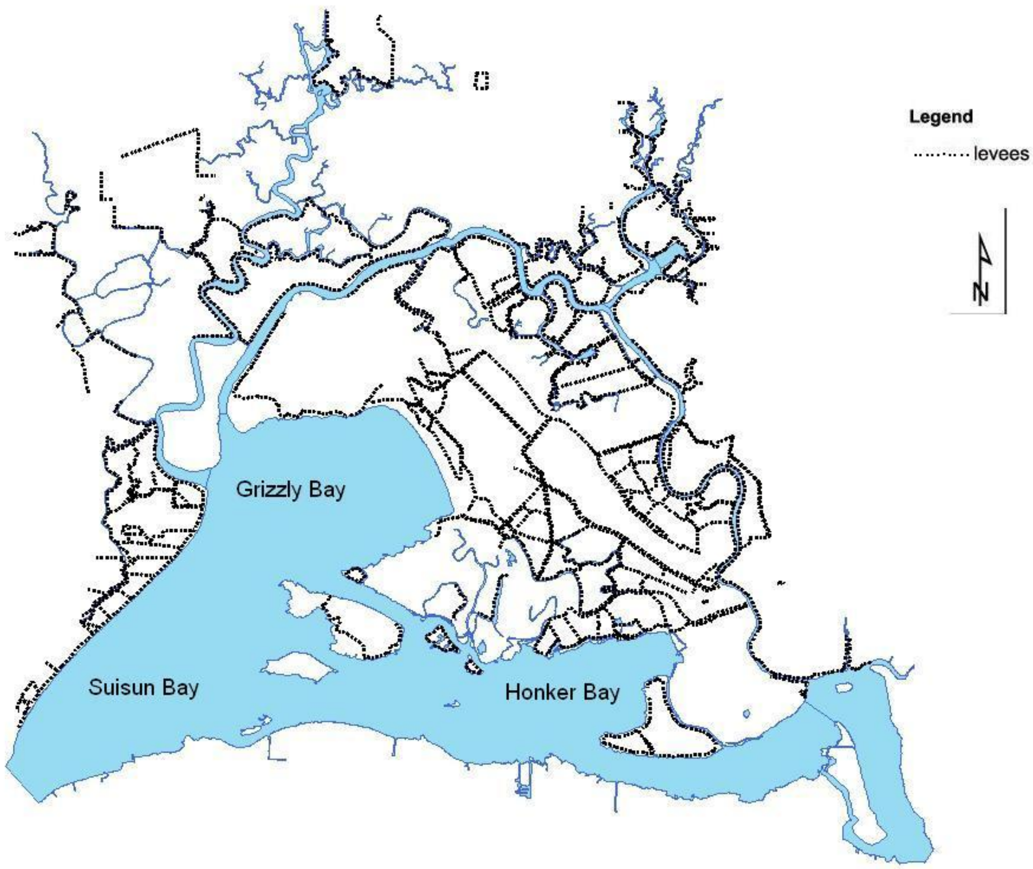
This Suisun Marsh levee conceptual model makes the following assumptions:

- The construction of levees in Suisun Marsh has resulted in the loss of tidal action on existing wetlands.
- Suisun Marsh levees are necessary to support tidal restoration goals and to protect existing habitats.
- The upland-like habitats provided by levees in Suisun Marsh have become essential components of this highly modified estuary.
- Improving levees will continue to provide long-term protection of managed wetlands, existing habitats, and help prevent salinity intrusion caused by levee failures.
- Levees are necessary for the continued protection of managed wetlands, county and state lands, infrastructure, residences, and prevention of salinity intrusion.
- Failure of levees in the marsh may flood areas that are not suitable for restoration as tidal wetlands.
- Failure of levees may flood diked wetlands, causing population declines of endangered species that occupy these habitats.

In describing the current state of knowledge, existing conditions, and effects of stressors on those conditions, the conceptual model is intended to be used as a tool in development of specific actions as part of the Suisun Marsh Plan. Although the model does not advocate specific maintenance or rehabilitation actions, it does identify research needs to address technical uncertainties and identifies recommendations to facilitate future actions that may be incorporated in the Suisun Marsh Plan or subsequent site-specific proposals as part of a comprehensive levee program in Suisun Marsh.

Levees as Habitat and Protection for Habitats

The Suisun Marsh levee system, a major component of the current marsh configuration, protects certain habitats and serves as habitat for some species. These levees provide flood protection for managed wetlands, county and state lands, infrastructure, residences, and habitat. They are on the front line in protecting water quality and various estuarine habitats from salinity intrusion. In addition to approximately 230 miles of exterior levees, many miles of interior levees were built to protect managed wetlands from flooding neighboring lands and to allow landowners to manage water quality and maintain their property for waterfowl habitat.



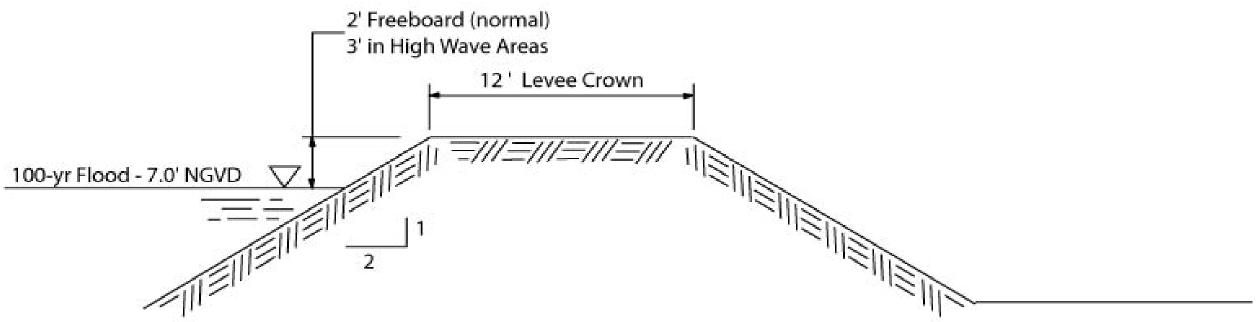
Suisun Marsh Levees
FIGURE 1

While the primary function of the Suisun Marsh levee system is to provide flood protection, over time habitat has developed along the levee waterside and landside slopes for native and introduced species. Fluctuating water levels on both the waterside and landside slopes creates opportunities and challenges for habitat management, preservation, and restoration. The interface along the waterside slope varies as tidal levels rise or fall covering or exposing larger areas of the levee slope. Similarly, the interface along the landside slope varies as water levels rise or fall as water control structures are used to regulate and manage draining and filling managed wetlands (SRCD, 1998). Common plant species growing along levees includes: annual grasses, blackberry, and coyote brush, and fennel. The Suisun song sparrow is commonly seen foraging or roosting in the shrubs along levees. The Suisun Marsh aster and Delta tule pea are often observed along the water's edge on the water side of Suisun Marsh levees. (USBR/DWR, 2004). The building of levees has changed the marsh landscape from its pre-European era condition, and over time levees have become an integral component of this highly modified estuary (Arnold, 1996; The Bay Institute, 1998).

Construction of levees during the late 1800's in Suisun Marsh for agricultural and waterfowl hunting resulted in the isolation of wetland habitat from tidal action as fill material was placed on existing wetlands to prevent flooding of adjacent lands (USFWS, 2004). The building and maintenance of levees over time has created a barrier between managed wetlands and adjacent waterways resulting in 67,700 acres of managed tidal wetland out of the original 74,000 acres (Arnold, 1996). Use of dredged material taken from adjacent channels for reinforcing levees over time has resulted in the deepening and widening of these adjacent channels. Many long-standing levees have been increased in size over time using dredged material and evolved into habitat for both native and introduced wildlife species. These levees can provide land/water interfaces at tidal water surface elevations which create habitat(s) for multiple estuarine species. Emergent aquatic and wetland plants and wildlife species use available habitat on the waterside levee slopes during various times of the year. Similarly, plant and wildlife species also use additional available habitats on the landside levee slope. The levee crown is typically maintained to allow vehicle and pedestrian access and is not widely considered valuable wildlife habitat; however, it may serve as transition or resting area between managed wetlands and adjacent waterways. Prospective removal of levees may not result in recovery of the initial habitat lost during original construction of levees and in fact may result in the loss of existing native or introduced species habitat that has developed on the constructed levee slopes.

Suisun Marsh levees are generally smaller than Delta levees in part because the magnitude of regional subsidence in Suisun Marsh has not been as great as that of the

Delta (Arnold, 1996). The levees have often been constructed along tidal channels using material dredged from adjacent waterways. Exterior levees in the Marsh have been built up progressively over the years, generally with little, or no, effort to design them to meet specific engineering standards (BDOC 1993). In fact, the standard Suisun Marsh levee configuration (Figure 2), was designed just over 20 years ago. This standard is approximately 4 feet narrower at the levee crown than standards used for US Army Corps of Engineers for levees on federal flood control projects (known as "Project Levees") or standards recommended by Department of Water Resources for agricultural lands in the Delta. Although most of Suisun Marsh land surface elevations are below sea level, levees in the marsh range in height from 4 to 8 feet above ground level are much smaller than those in the Delta where land surfaces are now 10-25 below sea level.



Standard Suisun Marsh
Exterior Levee Section
FIGURE 2

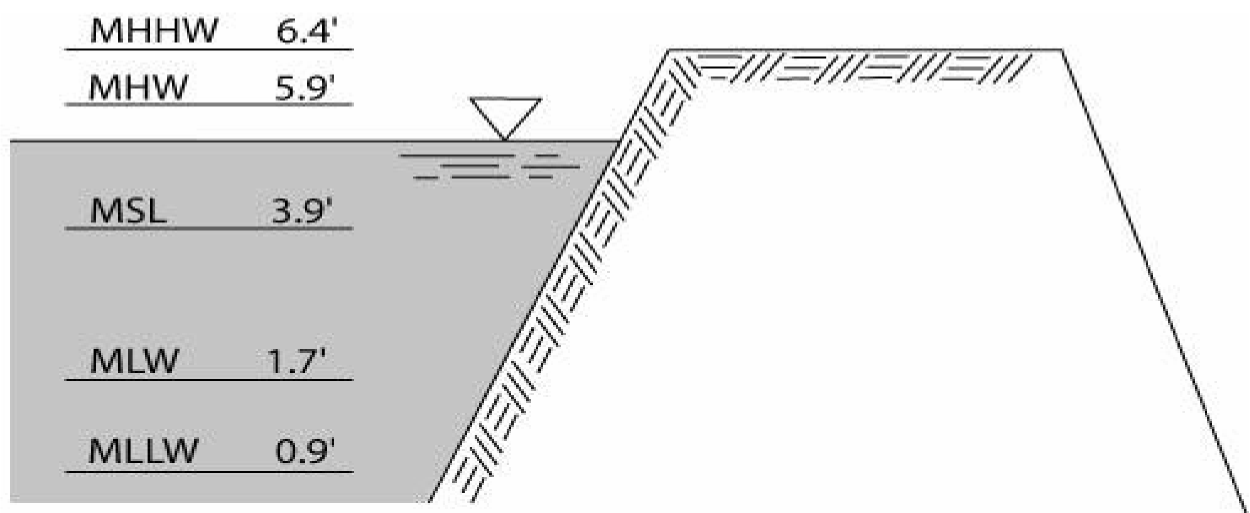
Fewer than 20 miles (between Van Sickle Island and the mouth of Montezuma Slough) of the exterior levees are eligible for levee maintenance assistance under the Delta Levees Maintenance and Subventions Program. Although the Suisun Marsh Levee Investigation Team identified a significant link between Suisun Marsh levees, water quality, and water supply reliability only a small portion considered to have the greatest impact on Delta salinities were included in Assembly Bill 360, Delta Protection and Delta Levee Maintenance. The approximately 210 remaining miles of exterior levees in the Suisun Marsh are not entitled to receive assistance under the Subventions Program for levee maintenance or flood fight activities. Maintenance and improvement of the Suisun Marsh levee system including interior levees is the responsibility of local Reclamation Districts, private wetland managers, California Department of Fish and Game (as manager of wildlife areas in Suisun Marsh), and Department of Water Resources (as responsibility for maintenance of several project facilities in the marsh).

In Suisun Marsh levee breaches due to winter weather and high tide flooding may be the most common type of flood event (such as that experienced during 1998). However, unexpected flooding and breaches at other times of the year (similar to the Jones Tract levee failure in the Delta in June 2004) occur in the marsh as well. The August 1999 breach at the Sunrise Club on Chadbourne Slough (280 acres) is an example of a small breach (180 feet in width) that had impacts on salinity within the marsh. Larger, region-wide breaches and flooding in the marsh, as in 1998, can have water quality effects in the Delta which can impact State Water Project and Central Valley Project operations (DWR 1999, 2000, 2001).

Natural and Anthropogenic Processes

This section describes natural and anthropogenic processes affecting levee stability. The natural processes are associated with tidal fluctuations in the Marsh and the anthropogenic processes are associated with maintenance and improvement activities for levees in the Marsh.

Suisun Marsh levees constantly experience the dynamic pressure of the fluctuating water levels on the waterside slopes that results in changes in soil structure and stability and can result in levee slumping or failure. Water levels in the marsh vary by about 6 feet from Mean Lower Low Water to Mean Higher High Water during each daily tidal cycle (BDAT, 2005). These water levels also vary seasonally and in conjunction with events such as storms and lunar cycles (see Water Quality Conceptual Model). In addition, sustained high water conditions, as experienced during 1998, can occur due to high runoff from upstream storm events. The ever-present and dynamic hydrostatic pressures on the levee slopes create opportunities for failure as described under the Stressors section below.



NAVD88 Tidal Datum for Tides at Bradmoor Island, Suisun Marsh
(NOAA Preliminary data, 2004)
FIGURE 3

Suisun Marsh levees are also under hydrostatic pressure due to fluctuating water levels on the landward side since managed wetlands are flooded using water control structures located within the levees (DFG/SRCD, 2004). Water control structures are built of culverts placed through the levee cross-section and usually include gates on one or both culvert ends. These control structures (sometimes referred to as “turnouts”) permit flow between managed wetlands and adjacent waterways. These structures rely on differing water levels and gravity to move water into ponds for flooding managed wetlands or to subsequently drain ponds to adjacent waterways.

Maintaining certain Suisun Marsh levees is necessary for continued flood protection of managed wetlands, county and state lands, infrastructure, residences, habitat, and water quality. Maintenance of levee crowns to provide year-round access for inspection purposes and levee slope maintenance can include placement of additional gravel, mowing, and clearing. Maintenance of landside slopes may include mowing, repair of slumping or eroded areas, rodent control, and spraying to control vegetation. Maintenance of waterside slopes is similar, except it is more restricted by physical and regulatory constraints, particularly where waterside slopes provide habitat or foraging areas for threatened and endangered species. Maintenance activities may also include cleaning of adjacent interior distribution ditches. Periodic maintenance of existing levees may affect local vegetation, result in habitat degradation or removal, and affect sensitive wildlife and plants within or near the repair sites. Maintenance activities are restricted in quantity and timing under the Regional General Permit from the USACE to eliminate impacts to threatened and endangered species.

Improvements to certain Suisun Marsh levees can increase flood protection. Levee improvement activities can include raising heights, repairing damaged sections, rebuilding levees, and/or extending landside slopes. Increasing heights protects against extreme tidal and flood events. Extending the landside slope further into managed wetlands improves levee stability and provides additional protection against seepage (Ramlit and Associates, 1983; DWR, 1995; Duncan and Wright, 2005). Other measures include bank protection with riprap and/or vegetation to reduce levee erosion. The loss of habitat resulting from these improvements can affect species that previously occupied levee slope areas. Although increasing the width and height of existing levees in certain areas to provide increased flood protection may result in impacts to critical habitat for State and federally threatened and endangered species, opportunities may exist to incorporate ecosystem components that result in net habitat improvements.

Suisun Marsh levees provide a physical barrier between public waterways and publicly- and privately-managed wetlands. These levees can limit boating access to privately managed wetlands and public lands by preventing boat traffic from entering lands directly via adjacent channels. Restricting public access can be beneficial to preservation goals or enhancement of habitats in Suisun Marsh where excess boating or pedestrian traffic conflicts with life history patterns of threatened and endangered species.

Levee Stability Stressors

Since tidal wetlands in Suisun Marsh were diked and reclaimed for agriculture and waterfowl management, many marsh properties have flooded at least once. Over time levees have exhibited deterioration or outright failure due to static and dynamic forces such as hydrostatic pressure, soil consolidation or settlement, overtopping, seepage/piping, and erosion (Ramlit and Associates, 1983). Other areas of increasing concern include: seismic vulnerability, land management (subsidence), and regulatory requirements.

Waves and Currents - Waves and tidal currents are the primary erosive forces on exterior levees. Unprotected exterior levee slopes may be undercut, scoured, or washed away. Erosive forces due to waves caused by wind fetch are particularly evident along the many miles of levees facing Honker and Grizzly Bays. Waves due to boat traffic along levees of sloughs or channels in the marsh also result in erosion of exterior levee slopes. Currents due to tidal or high runoff events can result in erosion of levee slopes, particularly during peak events.

Soil Consolidation - The marsh is underlain by thick layers of unconsolidated organic peat and bay muds, which have limited capacity to bear the weight of existing or enlarged levees (USDA, 1977; DWR 2001). These weak foundations exhibit significant consolidation over time as the weight of added levee material is not effectively supported by the existing underlying marsh peat soils. The depth and shear strength of these peat soils affect the static stability of levees, including improvement such as widening or raising heights. This problem is particularly significant in the southeastern part of the marsh where settling of levees may equal the height of the placed fill within months of placement. Levee rehabilitation plans should account for the unconsolidated nature of the foundation and its effect on maintenance and rehabilitation, including time required to complete repairs and/or improvements.

Subsidence – Observable subsidence in the marsh is a concern since lower ground surface elevations reduce levee stability and increases the risk of levee failures (DWR, 1995). Continuing subsidence is documented to a limited degree through benchmark elevation change observations. Private, state, and federal facilities and operations critical to maintaining ecosystem health, water quality, beneficial uses, and public safety are at increased risk as subsidence continues. In 1991, the USGS and the California Department of Water Resources began a study of the effect of different water management practices on carbon inputs and outputs and subsidence on Twitchell Island in the western Delta. The results of the study indicate that permanent flooding of peat soils can stop subsidence and increase the land-surface elevation (Deverel and Rojstaczer, 1996; Ingebritsen et al., 2000).

Overtopping - High water stages in the marsh can occur due to floods, unusually high tides, or atmospheric conditions involving high wind and low pressure. Not all levee sections in the marsh are sufficiently high to protect against overtopping during extreme tide or flood events (Ramlit and Associates, 1983). Some levee sections may erode or wash away from the scouring action of water flowing across the levee crown and down the landside slope.

Seepage/Piping - Movement of water through a levee caused by hydrostatic pressure against the water-side slope can result from construction with permeable material, poor post-construction maintenance, rodent burrowing, and soil cracking. Seepage through the levee may lead to flow-induced erosion and carrying away of material (piping), ever-enlarging seepage paths, and ultimately, levee failure (DWR, 1995).

Seismic Vulnerability - There is also growing concern that seismic vulnerability in the Delta and Suisun Marsh has been underestimated (Mount and Twiss, 2005). Unconsolidated marsh soils have limited capacity to bear the weight of levees and are vulnerable to seismic loading. The saturated soils in marsh wetlands may lose strength when subjected to ground shaking during an earthquake and result in levee foundation or slope failure(s). The frequency, intensity, and distribution of earthquake activity in Suisun Marsh along with the size, design, and vulnerability of existing levees are under review (Mount and Twiss, 2005).

Regulatory Requirements and Restrictions – Maintenance of Suisun Marsh levees falls under the jurisdiction or management of several agencies at the federal, State, and local levels (DFG/SRCD 2004). Current regulatory restrictions on time of year work can be done (timing), the quantity of work that can be done (volume), and location of work constrain the amount of work that can be undertaken in any given season. In addition, the preparation of permit applications and long review and approval times can be significant obstacles for initiating and completing work. For example, current regulatory requirements essentially eliminate the use of adjacent tidally-deposited sediments for levee rehabilitation and repair. However, use of imported material as a replacement requires concurrence from the Regional Water Quality Control Board prior to initiating any work. Regulatory constraints on maintenance and improvement activities for levees in the marsh may increase the potential risk for failure. This points out the direct conflict that exists between levees as habitat and levees as structures that provide flood protection.

Linkages

This section describes the interactions and potential conflicts between levee stability stressors and natural and anthropogenic processes described above.

Fluctuating water levels and dynamic hydrostatic pressure on levees can result in levee failure and loss of property and natural resources in Suisun Marsh. As demonstrated by the 1998 flooding and subsequent breach analysis computer modeling, Suisun Marsh and Delta salinity can be affected by levee failures in the marsh and can substantially affect California's water distribution and water quality reliability (DWR, 1999, 2000). Maintenance of levees can impact existing habitat and threatened and endangered species.

Management practices within Suisun Marsh managed wetlands can create conditions which contribute to the oxidation of bulk soil organic matter. Loss of this organic matter may lead to local and regional ground subsidence. The continuing subsidence of managed wetlands could affect levee stability and increase the risk of failure (DWR, 1995; Mount and Twiss, 2005). Levee improvements to counter this increased risk can cause conflicts with threatened and endangered species use of levee slopes for foraging or other needs.

Delays in approval of levee maintenance and repair permitting applications allows damage to continue to exist or worsen, which then can result in increased repair costs. Restrictions on the use of rip-rap (for levee maintenance) and the use of herbicides (to control vegetation) can result in the employment of alternative ongoing maintenance activities that may be more intrusive to threatened and endangered species. Once proposed maintenance work has received proper regulatory permitting, approved restrictions on timing, volume, and location of permitted activities often results in the proposed work being scheduled over several seasons, increasing overall maintenance costs and impacts to sensitive wildlife species.

Historically, leveeside dredging was typically done with either a clamshell or dragline dredge and provided a relatively inexpensive way of obtaining and placing fill material for levee maintenance and rehabilitation. The sloughs and channels adjacent to levees are subject to State and federal regulation since they provide habitat for special-status plants and animals. Restricting dredging activities results in use of landward sources of borrow material such as pond bottoms or material from distribution ditches. This material is typically high in organic content and less suitable for levee maintenance than bay mud.

Although this approach is more convenient and less expensive than importing material, it may result in reduced levee stability and contribute to subsidence. This approach may not be feasible in the long-term. Engineering principles and practical experience show that using mineral soils (dredged material from sloughs and channels) for levee construction and maintenance provides increased levee stability versus that provided by organic marsh soils. The lack of suitable material in the marsh for levee repairs results in increased costs, deferred maintenance, foregone improvements, and continuing impacts to species.

Technical Uncertainties and Research Needs

The technical uncertainties and research needs for levees in the Suisun Marsh include:

Technical Uncertainties	**Research Needs**
The extent and degree of impacts to SWP and CVP operations in the event of Suisun Marsh levee failure is uncertain.	Identification of which levees are most important to the protection of local and regional salinity, and what are their critical design features.
There is limited information on Suisun Marsh levee stability, including seismic vulnerability, composition of existing levees, geometric parameters such as slope, width, and length, geotechnical properties such as cohesion, angle of friction, in-situ compaction, factor of safety to withstand static and dynamic forces, especially in levees with weak foundations.	Additional research is needed on foundation materials in Suisun Marsh and effects on levee stability for proposed enlargements of existing levees.
The potential effects for species of concern by increasing levee size in certain areas to provide increased flood protection is uncertain. Project-type levee designs may provide more dependable water control and flood protection locally and regionally, but the environmental impacts and geotechnical constraints is uncertain.	Additional research is needed to evaluate if larger initial environmental impacts may be offset in the long-term through reduced maintenance requirements associated with reinforced levee slopes. At the same time, research is needed to evaluate if the larger volume of material needed can be effectively supported by the existing underlying Marsh peat soils.
The creation of waterside and landside levee berms on existing levees may provide areas that allow periodic flooding. It is uncertain if these areas will promote dense, tall, high marsh vegetation that can provide cover or tidal refugia for resident native marsh wildlife. It is also uncertain if the	Research on the design of levees with additional habitat features such as extended levee berms to provide opportunities to improve the level of flood protection and create needed habitat is needed. Research on the ability of dense vegetation growth on replacing the need for rip-rap is needed.

expected dense vegetation will reduce the efficiency of predator travel and foraging, and provide wind and wave protection.	
The timeframe new levee slopes will provide enhanced wildlife value over existing levee designs is uncertain.	Evaluation of the potential use of newly established upland-like habitat levee areas by terrestrial vertebrate predators and what are impacts to species of concern is needed.
Technical Uncertainties	**Research Needs**
The increase in risk for levees and the potential for increased incremental costs of local and regional sea level rise is uncertain.	Current and continuing studies of sea level rise should consider the associated effects on levees in Suisun Marsh. Research is needed to determine if natural geomorphic processes, such as local or regional sediment accumulation or erosion, can benefit levee program elements to an extent that will counter local or regional sea level rise.
Waterfowl management on managed wetlands differ considerably from agricultural practices in the Delta. The contribution of this management to subsidence in the marsh, and its effect on levee stability is uncertain. It is uncertain if subsidence is a local, regional, or tectonic phenomenon.	Research is needed on management practices that can reduce, eliminate, or mitigate for ongoing subsidence. Research is needed to determine the cause as well as the individual and cumulative effect of subsidence and sea level rise on levee stability.
The cost share allocation for future levee maintenance and improvements is uncertain. The beneficiaries of the levee system and how should they contribute is uncertain.	Research is needed to determine the beneficiaries for maintenance, improvements, and environmental costs of optimum designs and layouts for successful implementation. An evaluation of an incentive program that will encourage conservation practices and/or appropriate levee design and placement that can reduce overall programmatic cost, habitat impacts, and future risk is needed.
The level of federal and state support for protection of private landholdings in light of potential need for water quality and habitat protection needs *in perpetuity* is	Additional research is needed as follow-up to the linkages identified by the CALFED Levee Program between the Suisun Marsh levee system configuration and water

uncertain.	quality in the Delta. (CALFED Suisun Marsh Levees Investigation Report, March 2001)
Technical Uncertainties	**Research Needs**
What control measures are available for use in the near-aquatic and aquatic environments, who can implement them, and how effective are they is uncertain.	Experience with restoration projects in the Delta and elsewhere within the San Francisco Estuary has shown that substantial efforts will be needed to reduce the impacts of non-native invasive species, particularly invasive weedy plants.
It is uncertain how large quantities of material to meet the requirements for levee maintenance and improvements will be provided. It is uncertain how channel dredging will affect channel geomorphology and levee stability.	Research is needed in developing a strategy for utilizing dredge material collected within Suisun Marsh and from adjacent waterways as well as alternative sources. Research is needed on determining effects of dredging on fisheries rearing, spawning, and migration habitat in tidal sloughs.

Conclusions/Recommendations:

Local, Statewide and national resources depend upon maintenance of an effective levee system in Suisun Marsh. Building and maintaining dependable flood protection structures (levees) and minimizing the negative environmental impacts of levee maintenance and construction will be required in order to meet conflicting needs for protection of human and natural resources.

The following recommendations are made to reduce levee vulnerability and reduce the risk of future failures and loss of valuable wildlife resources:

- The current inability to pinpoint which levees are critical to the levee system in Suisun Marsh suggests completing a risk analysis for levee failures in the marsh. Identify which levees are critical to protection of water quality, wildlife habitats, and other resources. Identify beneficiaries and the costs of necessary maintenance and improvements.

- The value of wetland habitat on natural berms and levees should be evaluated for potential incorporation in future projects. Although the use of levees as transition areas from tidal to upland or upland-like habitats may be desirable ecologically, any evaluation should include assessing the potential predation from upland resource areas on aquatic or near-aquatic species.

- An emergency management plan is necessary to protect managed wetlands, residences, and infrastructure. This plan should include details outlining responsibilities and coordination for agencies and landowners such as management and mobilization of resources, emergency repair activities, and who pays for emergency management for flooding on public and private lands.

- The establishment of a Beneficial Re-use Program for dredge material is necessary for levee maintenance throughout the marsh. Additional demonstration projects similar to Montezuma Wetlands are needed to evaluate the feasibility of using ship channel dredge material in the marsh for levee maintenance and improvements.

- The establishment of an updated precision elevation benchmark network and a subsidence monitoring program throughout the marsh are needed to evaluate continuing subsidence, the potential for tidal wetland restoration, and the maintenance and improvement of levees.

- Increased coordination among ongoing levee maintenance and rehabilitation activities, including development of a marsh wide levee survey. Sharing of existing data, knowledge, and experience will assist in identifying critical areas, developing costs for maintenance and improvements, and pursuing necessary research as part of a long-term levee program in Suisun Marsh.

- Evaluation of a cost-share program to encourage moist soil management and incentives for encouraging participation should be pursued. Moist soil management would promote wet conditions during the spring and summer to prevent excessive loss of gaseous carbon, more carbon accumulates than is lost, similar to conditions when the peat soils were formed.

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